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Effect of Pyrolysis Temperature on the Adsorption of Cr(VI) on Biochar Prepared from Millet Straw

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Abstract

As a highly toxic and hazardous chemical element, even in low concentration, chromium (Cr), which is mostly exists as a trace metal either as Cr^{3+} or Cr^{6+} cause serious humans health problems such as, carcinogenic (skin cancer, lung cancer) skin irritation, kidney dysfunction, liver failure, and anemia. This study is aimed at adsorption Cr(VI) from aqueous solution using millet straw biochar (BCM) produced by slow pyrolysis at four different temperatures (300 to 600) ^{o}C. Batch adsorption process was conducted, and the adsorption ability of BCM was assessed under optimum conditions of pH (2-10), concentration (30-200) mg/L, biochar dosage (0.3-1.1) g, contact time (318, 323, 328, 333) K. The result showed higher adsorption of Cr(VI) at low pH of 2. However, increasing the adsorbent dosage, also increased the maximum adsorption of Cr(VI). Furthermore, the result demonstrated that, an increase in solution concentration, the adsorption capacity also increases significant ($p<0.05$), before it eventually started to decrease when the BCM surface become saturated at 100 mg/L for Cr^{6+} and was considered optimum conditions. Furthermore, the Q_{max} of Cr(VI) was strongly influenced by the abundance of surface oxygen-containing functional groups, resulting in high Langmuir affinity parameter (R_L) values. This confirms that chemical affinity rather than surface area controlled Cr^{6+} adsorption on BCM, particularly at lower pyrolysis temperatures. **BCM** typically exhibit adsorption kinetics dominated by chemisorption adsorption processe**s**. The relatively higher retention of oxygen-containing functional groups promotes strong interactions with Cr (VI) ions through surface complexation. Hence, adsorption kinetics for BCM often describe well by pseudo-second-order (PSO). Subsequently, ΔG becomes increasingly negative with increasing temperature, demonstrating that the adsorption process is more spontaneous at high temperatures. This suggests that the adsorption of Cr(VI) can occur more efficiently with increasing temperature. Therefore, BCM is an eco-friendly adsorbent that can serve as alternative adsorbent for the remediation of contaminants from the environment.

Keywords: biochar, millet straw, batch adsorption, Langmuir, Pseudo-second order

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1. Introduction

Naturally, chromium (Cr) mostly exists as a trace metal either as Cr^{3+} or Cr^{6+} with oxidation states of +3 and +6 respectively. However, the latter is form when the former is naturally released and oxidized (Abdulkadir & Garba, 2024). However, Cr^{6+} is water soluble and highly reactive (Ghani *et al.*, 2022). A non-biodegradable and toxic metal, Cr^{6+} often behaves as cation and anion in water (Musah *et al.*, 2018). Industrial activities such as textile and dyeing, leather and tanning processing, are among the most major source of Cr^{6+} into the environment especially water bodies (Rajoriya *et al.*, 2020). As a highly toxic and hazardous chemical element, even in low concentration, Cr^{6+} cause serious humans health problems such as mutagenic, carcinogenic, skin irritation, lung cancer, kidney dysfunction, liver failure, and anaemia (Fito *et al.*, 2023; Ghani *et al.*, 2022).

Biochar, a product of biomass generated by slow pyrolysis (300 - 700 ºC) temperature in an insufficient oxygen, is enriched carbon material (Yang *et al.*, 2024). Biochar has been considered as cost friendly biosorbent (Li, 2020). It is considered potential adsorbent due to its high surface area, porous structure and abundant functional group (Di *et al.*, 2025). Hence, the applications of biochar particularly, in environmental pollution remediation is as a result of these properties (Syarifuddin *et al.*, 2024).

In this study, biochar was prepared from millet straw (BCM) at pyrolysis temperature of 300- 600 ºC. The aim of the present work is to determine the influence of temperature on the adsorption of Cr(VI) present in aqueous solutions, using waste millet straw.

2. Materials and methods

2.1. Sourcing and preparation of feedstock

The agricultural waste (millet straws) (2kg) was collected randomly from selected sampling area after harvest in local farms of Imawa in Kura, which lies on approximately -11.7678° N latitude, and longitude- 8.4263 E of Kano state, Nigeria. The biomass was then bulked together to form a composite sample, packaged into polyethylene bags and transported to laboratory for further preparation and analysis (Mohammed *et al.*, 2011).

2.2. Biochar production and characterization

Details of biochar production and characterization (BET-surface area, FTIR, SEM, XRD, pHpzc, CEC, and elementals (C, H, O, and N) experiments have been extensively described in our previous publications (Abubakar *et al.*, 2025). The generated biochar produced at four different pyrolysis temperature 300, 400, 500, and 600 °C were designated as BCM300, BCM400, BCM500, and BCM600.

2.3. Batch Adsorption Studies

Comprehensive procedures on the effect of pH (2-10), concentration (30 to 250 mg/L), adsorbent dose 0.3 to 1.1 g), effect of time of contact (30 to 120 minutes) and temperature effect (35 to 60 °C) have been provided in our previous work (Abubakar *et al.*, 2025). Maximum adsorption capacity (q_e) and removal efficiency (R) of BCM for Cr(VI) was calculated using equations (1) and (2), respectively:

$$qe(\text{mg/g}) = \frac{Ci-Ce}{w}\text{x}V \qquad (1)$$

$$\%\ \text{Removal effeciency} = \frac{\mathbf{Ci-Ce}}{\mathbf{Ci}}\text{x}100 \qquad (2).$$

Where: w (g) is the weight of biochar, V (L) is the volume of solution, and Ci and Ce(mg/L) are initial and equilibrium concentrations of Cr (VI) in solution, respectively.

2.3.1. Adsorption Isotherms

Isotherm models (Langmuir, Freundlich and Temkin) models were investigated from the adsorption data obtained from the effect of concentrations of Cr(VI) onto the biochar (Ata *et al.*, 2023; Hu *et al.*, 2025). The nonlinear forms of the Langmuir, Freundlich and Temkin models are given in equations (3), (4) and (5), respectively:

$$qe = \frac{qmKLCe}{1+KLCe} \qquad (3)$$

By plotting of $\frac{Ce}{qe}$ $versus\ Ce,$ qmax and K_L can be determined from the slope and intercept

$$R_L = \frac{1}{1+CiKL}$$

$$qe = K_F Ce^{1/n} \qquad (4)$$

$$q_e = B\ln(K_T C_e) \qquad (5)$$

Where: K_L = Langmuir constant (mg/L), dimensionless separation factor (R_L) ; however, $R_L > 1$: Unfavourable adsorption, $R_L = 1$: linear adsorption, $0 < R_L < 1$: favourable adsorption, $R_L = 0$: Irreversible adsorption. K_F: Freundlich constant, indicative of adsorption capacity (mg/g), K_T: Temkin constant related to the binding energy, R is the gas constant 8.314 J/mol$^-$K, T is the temperature K and b is a parameter representing the heat of adsorption.

2.3. 2. Adsorption kinetics

Kinetic analysis of the adsorption process was performed using time intervals of 5, 5, 10, 15, 20, 30, 60, 90, and 120 minutes. However, pseudo-first-order, pseudo-second-order and Elovich kinetic models were fitted to determine the best model that describe the adsorption kinetic process. The non-linear forms of the models are presented in equations (6) to (8):

$$q_t = q_e(1 - e^{-kt}) \text{ (Pseudo-first-order)} \quad (6)$$

$$qt = \frac{q_e^2 k_2 t}{1+q_e k_2 t} \text{ (Pseudo-second-order)} \quad (7)$$

$$q_t = \frac{1}{\beta}\ln(1 + \alpha\beta t) \text{ (Elovich models)} \quad (8).$$

Where : $\boldsymbol{q_e}$ the quantity adsorbed at equilibrium (mg/g) by the biochar, $\boldsymbol{q_t}$: The quantity adsorbed at time t (mg/g), K_1 and K_2 are the Pseudo-second-order and pseudo second order rate constant (gm/g. min), respectively, the values of the rate constant $\boldsymbol{k_1}$, $\boldsymbol{k_2}$ and adsorption capacity $\boldsymbol{q_e}$ (mg/g) were obtained from the slopes and intercepts of the plots of $ln(q_e - q_t)$ versus t, respectively. t: Time (min), (min^{-1}). α: Initial adsorption rate (mg/g.min) and β: Desorption constant related to the extent of surface coverage and activation.

2.3.3. Adsorption thermodynamic

Thermodynamic experiments were performed at 318, 323, 328 and 333 K. Thermodynamic parameters such as free energy changes (ΔG, J mol^{-1}), enthalpy changes (ΔH, kJ mol^{-1}), and the entropy changes (ΔS KJ mol^{-1} K^{-1}) associated with the adsorption process was calculated using the relationship given in the following equations **(**9**)** to **(**11**)**:

$$K_D = \frac{\boldsymbol{qe}}{\boldsymbol{Ce}} \quad (9)$$

$$\Delta G = -RTlnK_D \quad (10)$$

$$\ln K_D = \frac{\boldsymbol{\Delta H}}{\boldsymbol{RT}} - \frac{\boldsymbol{\Delta S}}{\boldsymbol{R}} \quad (11)$$

3. Results and discussion

3.1. Effect of pH on adsorption of Cr(VI) ion

Solution pH has greater impact on the maximum adsorption of metal ions by adsorbents as it determine the adsorbent active sites (Elyahyaoui *et al.*, 2017; Zhao *et al.*, 2020; Osman *et al.*, 2024). Figure 1 presents the profile on effect of pH on the adsorption of Cr(VI) by BCM at four different pyrolysis temperature. From the result it can be observed that the biochar adsorbed maximum Cr(VI) ion at pH 2. The Cr(VI) maximum adsorption at acidic conditions, might be attributed to the protonation of biochar surface (Abubakar *et al.*, 2025). Furthermore, from the result it can be predicted that neutral alkaline wastewaters or Cr(VI) contaminated water, a high-temperature BCM is preferable (Zhao *et al.*, 2020).

3.2. Effect of adsorbent dose on adsorption of Cr(VI) ions

The biochar dose is another critical factor in determining metal ions removal efficiency. This is because, number of available adsorption sites, which determine the degree of adsorbent-adsorbate interaction is more or less control by adsorbent dosage (Tian *et al.*, 2022). The result of the BCM dose on Cr(VI) adsorption is shown in (Figure 2). The result showed a considerable decreased in the uptake of Cr(VI) at high adsorbent. This is because higher adsorbent dosage overwhelmingly reduces the saturation of active sites (Mutanekelwa *et al.*, 2022). Thereby reducing the number of covered sites per unit mass of adsorbent (Reddy, 2019). Moreover, increase in adsorbent mass in solution means increased the accumulation of particles which block the pores structures leading to the reduction of the adsorbent specific surface area and increases which disagreeably affect adsorption capacity (Ghani *et al.*, 2022).

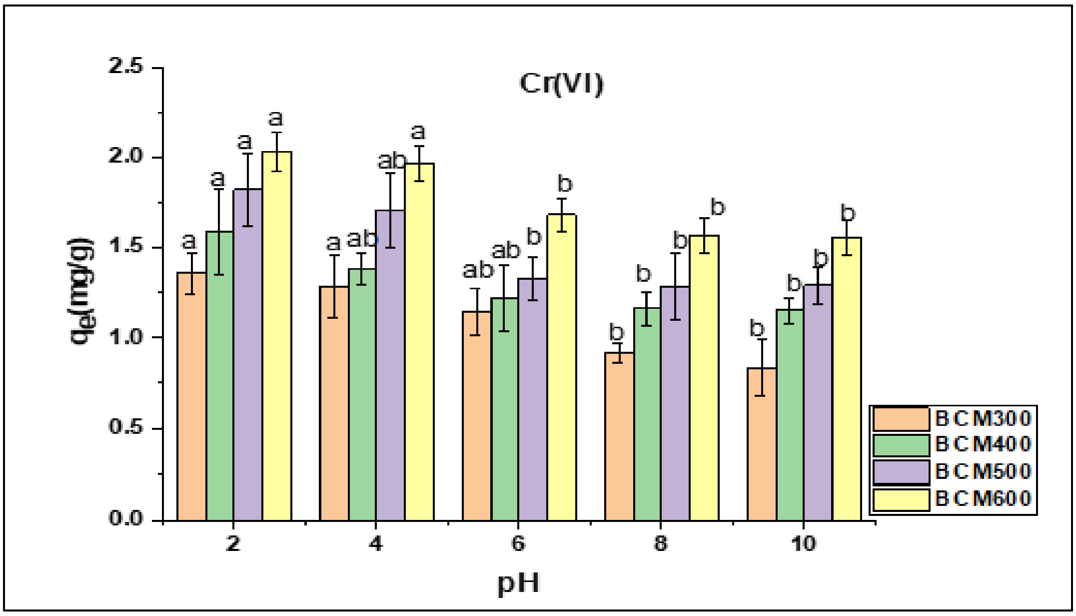

Figure 1. Effect of pH on the adsorption capacities of Cr(VI) onto BCM

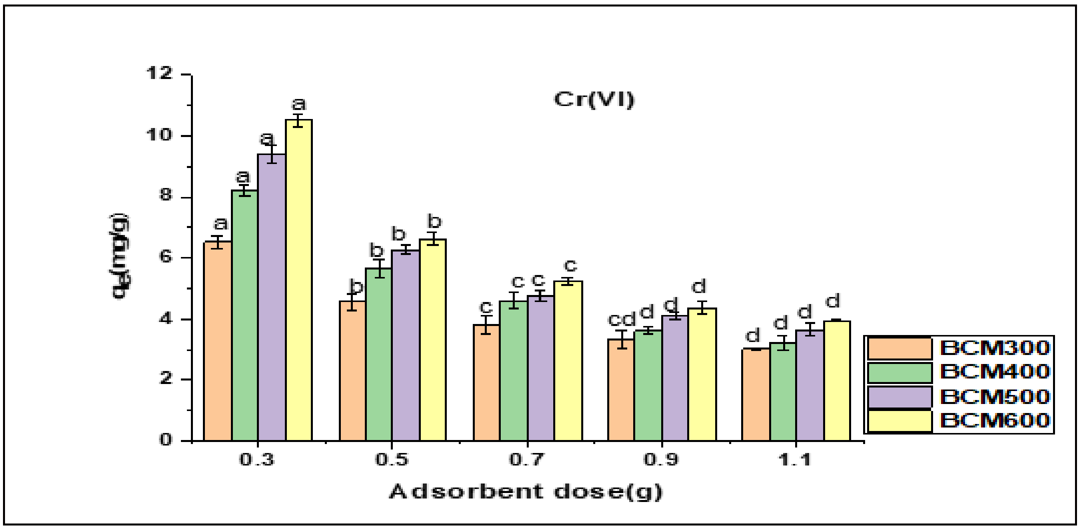

Figure 2. Effect of BCM dosage

3.3 Adsorption isotherm

The initial concentration impact on adsorption capacity of Cr(VI) by BCM was examined in the concentration ranges of 30 to 200 mg/L. The result is presented in (Table 1) and (Figure 3). The result showed an increase in solution concentration, the adsorption capacity also increases significant ($p<0.05$)

increased, before it eventually started to decrease when the BCM surface become saturated at 100 mg/L for Cr^{6+} and was considered optimum conditions. Meanwhile, from the result it was also observed, despite the presence of oxygen-containing functional groups, the higher volatile matter and the absence of well-developed mineral phases (Gayathri et al., 2021) that biochar produced at low pyrolysis temperatures (300–400 °C) exhibited comparatively low maximum adsorption capacities (Q_{max}) (Table 1), this is due to incomplete carbonization, limited pore development, and low surface area (Abubakar, 2026). Furthermore, the Q_{max} of Cr(VI) was strongly influenced by the abundance of surface oxygen-containing functional groups, resulting in high Langmuir affinity parameter (R_L) values (Figure 3). This confirms that chemical affinity rather than surface area controlled Cr^{6+} adsorption on BCM, particularly at lower pyrolysis temperatures (Singh and Bhateria, 2020).

Table 1. Non-linear Langmuir, Freundlich and Temkin Isotherm adsorption parameters for Cr(VI) onto BCM at four different pyrolysis temperatures.

Metal	**Biochar**		**Langmuir**			**Freundlich**			**Temkin**		
		$Q_{e\ exp.}$	**$Q_{max.}$**	**K_L**	**R^2**	**K_F**	**n**	**R^2**	**B_T**	**K_T**	**R^2**
Cr(VI)	BCM300	7.90	8.09	0.0097	0.999	1.68	3.039	0.839	2.02	0.47	0.92
	BCM400	8.17	8.37	0.0104	0.998	1.87	3.184	0.829	2.03	0.53	0.91
	BCM500	8.23	8.66	0.0098	0.996	1.97	3.310	0.824	2.09	0.55	0.91
	BCM600	8.86	9.02	0.012	0.998	2.04	3.311	0.846	2.16	0.56	0.92

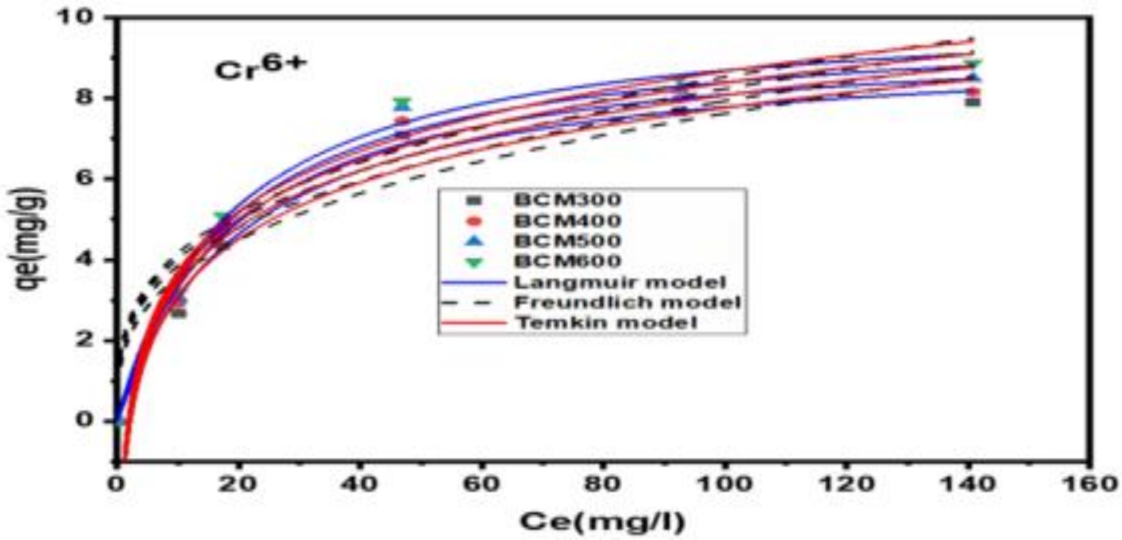

Fig 1. Non-linear Langmuir, Freundlich and Temkin isothermal models for adsorption of Cr^{6+} onto BCM

3.4. Adsorption kinetics

The results of the effect of contact time on the Cr(VI) uptake by BCM at four different temperatures is presented in Figure 4. The result showed that the process occurred in three discrete stages. That is at the first 15 minutes, the Cr(VI) uptake was rapidly. This is due to the fact that at the beginning of the process, the external surface sites of the adsorbent occupied quickly (Cuixia *et al*., 2020). However, the process continues the adsorption gradually become slower, this is attributed to the limited concentration gradient and potential pores diffusion rate, in this stage, the adsorption sites are occupied over the time. Subsequently, as the adsorption time continues, the processes approach equilibrium after 90 minutes, which indicates that the saturation reached, and that the rate of adsorption equals rate of desorption (Wang *et al*., 2025). However, from (Figure 4) and (Table 2), it can be observed that adsorption Cr(VI) by BCM is typically dominated by chemisorption-controlled processes**.** This might be attributed oxygen-containing functional groups which promotes strong interactions with metal ions through surface complexation and ligand exchange (Singh & Bhateria, 2020). BCM typically exhibit adsorption kinetics dominated by chemisorption-controlled processes**,** particularly at low to intermediate pyrolysis temperatures. The relatively higher retention of oxygen-containing functional groups promotes strong interactions with metal ions through surface complexation and ligand exchange. Consequently, adsorption kinetics for BCM often conform well to the pseudo-second-order (PSO) model, reflecting the chemical nature of the rate-limiting step.

Table 2. Non-linear Pseudo-first order (PFO), Pseudo-second order (PSO), and Elovich kinetic model's adsorption parameters for Cr(VI) onto BCM at four different pyrolysis temperatures.

Metal	**Biochar**	**Pseudo-first order**				**Pseudo-second order**			**Elovich**			
		$q_{e\ exp.}$	$q_{ecal.}$	K_1	R^2	$q_{ecal.}$	K_2	R^2	$q_{ecal.}$	a	b	R^2
	BCM300	6.99	6.83	0.325	0.820	7.08	0.1116	0.999	6.99	5.60	2.12	0.999
Cr (VI)	BCM400	7.34	7.08	0.359	0.770	7.34	0.1215	0.999	7.33	1.99	2.029	0.999
	BCM500	7.70	7.43	0.323	0.760	7.76	0.0954	0.999	7.70	15.99	2.003	0.999
	BCM600	7.80	7.60	0.354	0.840	7.88	0.1135	0.999	7.81	3.65	2.119	0.999

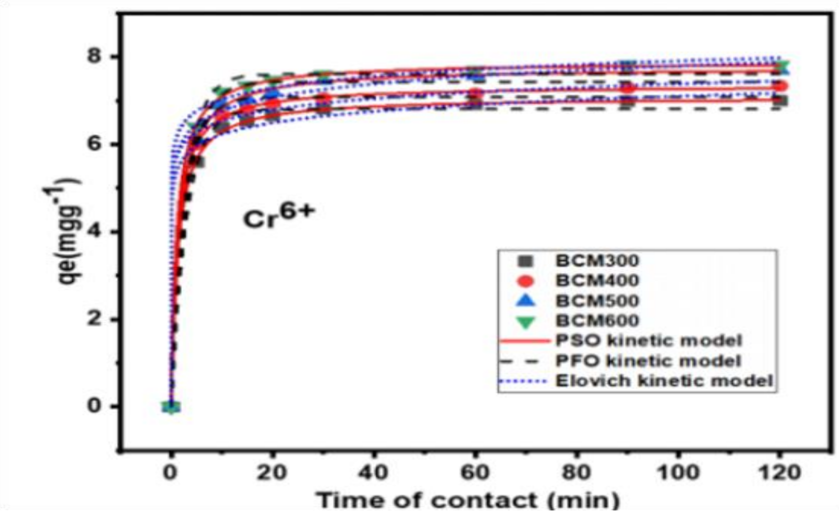

Fig. 4 Non-linear Pseudo-first order (PFO), Pseudo-second order (PSO), and Elovich kinetic models for adsorption of Cr^{6+} onto BCM

3.5. Adsorption thermodynamic

Temperature has greater impact on the adsorption capacity, as it affect the physicochemical properties of adsorbent (Ata *et al.*, 2023). Table 3 and Figure 4 present the result of the effect of temperature of BCM on the adsorption of Cr(VI). The results showed a positive enthalpy change ($\Delta H° > 0$), this indicates that the adsorption process is endothermic**,** meaning that adsorption is favoured at higher temperatures (Ata *et al.*, 2023). This suggests that the adsorption of Cr(VI) by BCM required energy to overcome barriers such as dehydration, specific chemical interaction**,** diffusion into internal pores, or restructuring of surface sites before effective adsorption can occur (Nguyen *et al.*, 2025).

Table 3: Thermodynamic Parameters for Adsorption of Cr(VI) onto BCM

Biochar	Temperature (K)	ΔG ($Jmol^{-1}$)	ΔH($Jmol^{-1}$)	ΔS ($KJmol^{-1}$)	R^2
BCM300	318	-138.95	1974	62.52	0.99
	323	-486.63			
	328	-725.93			
	333	-1101.67			
BCM400	318	-318.67	2368	75.38	0.95
	323	-698.94			
	328	-926.38			
	333	-1503.22			
BCM500	318	-616.95	2698	86.68	0.99
	323	-973.89			
	328	-1423.94			
	333	-1914.29			
BCM600	318	-891.47	3248	104.81	0.91
	323	-1422.07			
	328	-1657.09			
	333	-2567.65			

The positive entropy change ($\Delta S° > 0$) also observed implies an increase in randomness at the solid–solution interface during adsorption. Although adsorption is often intuitively associated with decreased disorder, in aqueous systems this apparent contradiction is resolved by considering the desolation of hydrated metal ions (Hu *et al.*, 2025). When metal ions bind to biochar surfaces, structured water molecules surrounding the ions are released into the bulk solution, and increase freedom of the displaced ions (e.g., Ca^{2+}, H^+) released via ion exchange as well as the large positive ΔS, suggests a greater increase in randomness, after associated with process involving ion exchange or dehydration, resulting in a net increase in entropy (Singh & Bhateria, 2020). Subsequently, ΔG becomes increasingly negative with increasing temperature, demonstrating that the adsorption process is more spontaneous at high temperatures. This suggests that the adsorption of Cr(VI) can occur more efficiently with increasing temperature (Guo *et al.*, 2020).

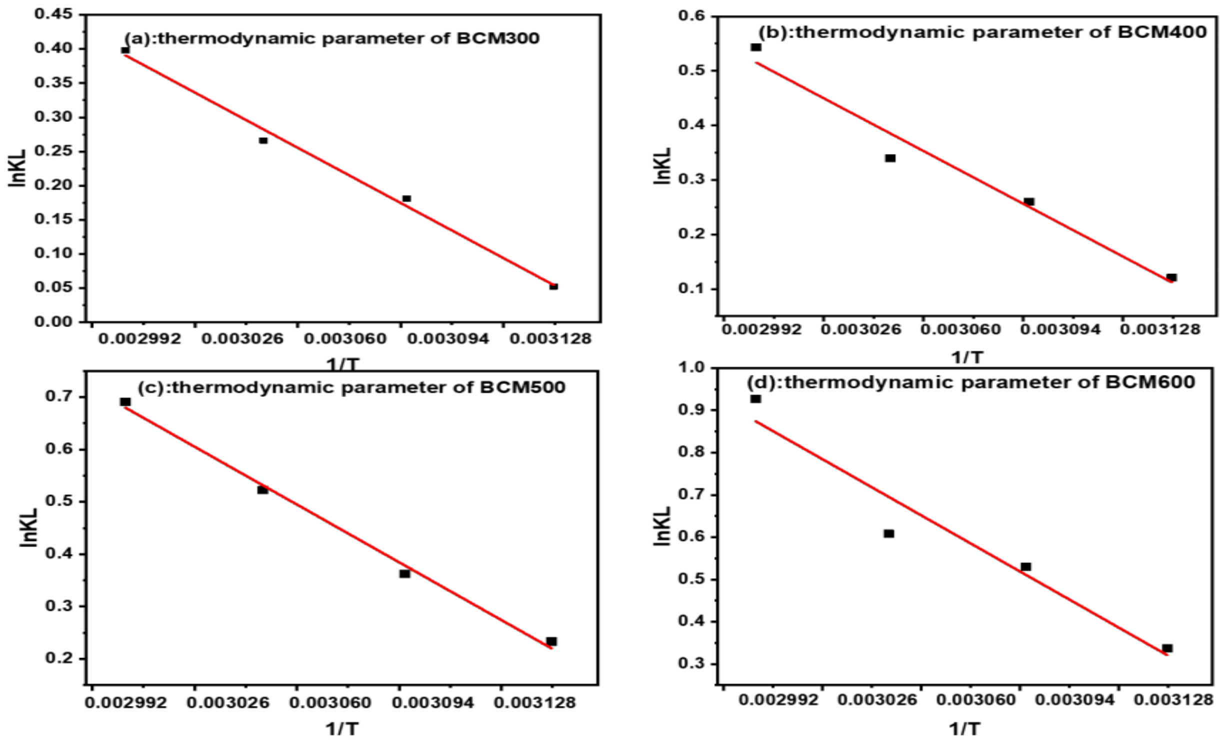

Fig.4 Van't Hoff's plot for the adsorption of Cr(VI) onto BCM

Conclusion

Agricultural wastes as biomass for biochar production continue to attract researcher interest. Biochar produced from millet straw by slow pyrolysis to be applied as an adsorbent for the remediation of water contaminated Cr(VI) was investigated. The generated biochar exhibited lower to moderate surface area, moderate functional groups, higher carbon and ash contents, all which are good characteristics of an adsorbents. Adsorption of Cr(VI) by BCM demonstrated that at pH 2, the Cr(VI) adsorption was higher. Also, increasing the adsorbent dosage, also increased the maximum adsorption of Cr(VI). Furthermore, the result demonstrated that, an increase in solution concentration, the adsorption capacity also increases significant ($p<0.05$), before it eventually started to decrease when the BCM surface become saturated at 100 mg/L for Cr^{6+} and was considered optimum conditions. Furthermore, the Q_{max} of Cr(VI) was strongly influenced by the abundance of surface oxygen-containing functional groups, resulting in high Langmuir affinity parameter (R_L) values. This confirms that chemical affinity rather than surface area controlled Cr^{6+} adsorption on BCM, particularly at lower pyrolysis temperatures. BCM typically exhibit adsorption kinetics dominated by chemisorption adsorption processes. The relatively higher retention of oxygen-containing functional groups promotes strong interactions with Cr (VI) ions through surface complexation. Hence, adsorption kinetics for BCM often describe well by pseudo-second-order (PSO). Subsequently, ΔG becomes increasingly negative with increasing temperature, demonstrating that the adsorption process is more spontaneous at high temperatures. This suggests that the adsorption of Cr(VI) can occur more efficiently with increasing temperature.

Conflict of Interest

The authors declare that there are no conflicts of interest

References

Abdulkadir, Y., & Garba, F. (2024). Process For Chromium (VI) Removal From Mechanized Tannery Wastewater Using Activated Carbon Obtained From Tannery Solid. *Fudma Journal of Sciences (FJS)*, *5*(1), 364–371. https://doi.org/10.33003/fjs-2021-0501-577

Abubakar, I. (2026). *Adsorption of Cd (II) ion from aqueous solution using biochar derived millet straw*. *13*(3), 518–529.

Abubakar, I., Saeed, M. D., & Ayuba, A. M. (2025). Effect of Pyrolysis Temperature on Characteristics and Adsorption of Pb (II) onto Millet Straw Derived Biochar from Aqueous Solution. *Arabian Journal of Chemical and Environmental Research*, *12*(2), 80–99.

Ata, S., Tabassum, A., Shaheed, I., Mohsin, I., Alwadai, N., Huwayz, M. Al, Iqbal, M., & Nazir, A. (2023). Adsorption Thermodynamics , Modeling , and Kinetics Studies for the Removal of Lead Ions Using ZnO Nanorods. *Adsortion Science and Technology*, *2023*, 1–10.

Cuixia, Y., Yingming, X., Lin, W., Xuefeng, L., & Yuebing, S. (2020). Effect of different pyrolysis temperatures on physico-chemical characteristics and lead(II) removal of biochar derived from chicken manure. *Royal Society of Chemistry*, *10*, 3667–3674. https://doi.org/10.1039/c9ra08199b

Di, D., Xiao, J., Zhao, B., Chen, Y., Song, Z., & Chen, G. (2025). Immobilization of Cd (II) by phosphorus - modified bamboo biochar from solution : mechanistic study from qualitative to quantitative analysis. *Carbon Research*, *4*(35). https://doi.org/10.1007/s44246-025-00196-7

Elyahyaoui A, Ellouzi K, Al Zabadi H, Razzouki B, Bouhlassa S, Azzaoui K, Mejdoubi EM, Hamed O, Jodeh S, Lamhamdi A. (2017). Adsorption of Chromium (VI) on Calcium Phosphate: Mechanisms and Stability Constants of Surface Complexes. *Applied Sciences.* 7(3), 222. https://doi.org/10.3390/app7030222

Fito, J., Abewaa, M., & Nkambule, T. (2023). Magnetite - impregnated biochar of parthenium hysterophorus for adsorption of Cr (VI) from tannery industrial wastewater. *Applied Water Science*, *13*(3), 1–23. https://doi.org/10.1007/s13201-023-01880-y

Gayathri, R., Gopinath, K. P., & Kumar, P. S. (2021). Adsorptive separation of toxic metals from aquatic environment using agro waste biochar : Application in electroplating industrial wastewater. *Chemosphere*, *262*, 128031. https://doi.org/10.1016/j.chemosphere.2020.128031

Ghani, U., Jiang, W., Hina, K., Idrees, A., & Iqbal, M. (2022). Adsorption of Methyl Orange and Cr (VI) Onto Poultry Manure-Derived Biochar From Aqueous Solution. *Frontiers in Environmental Science*, *10*(June), 1–13. https://doi.org/10.3389/fenvs.2022.887425

Guo, X., Liu, A., Lu, J., Niu, X., Jiang, M., Ma, Y., Liu, X., & Li, M. (2020). Adsorption Mechanism of Hexavalent Chromium on Biochar : Kinetic , Thermodynamic , and Characterization Studies. *American Chemical Science Journal*, (2013). https://doi.org/10.1021/acsomega.0c03652

Hu, J., Yang, S., Ma, P., & Deng, Z. (2025). Adsorption of Cu (II), Pb (II), Cd (II), and Cr (III) from aqueous solutions using modified coffee grounds biochar. *Desalination and Water Treatment*, *323*(June), 101262. https://doi.org/10.1016/j.dwt.2025.101262

Huseyn Osman, Mehmet Uğurlu, Ali İmran Vaizoğullar, Muhammet Atasoy, A. J. C. (2024). *Statistical modeling and optimization of heavy metals (Pb and Cd) adsorption from aqueous solution by synthesis*. https://doi.org/10.1007/s00289-024-05404-9

I. Sreedhar N. Saketharam Reddy. (2019). Heavy metal removal from industrial effluent using bio - sorbent blends. *SN Applied Sciences*, *1*(1021), 1–15. https://doi.org/10.1007/s42452-019-1057-4

Li, Y. (2020). Adsorption behaviors on trace Pb 2 þ from water of biochar adsorbents from konjac starch. *Adsortion Science and Technology*, *38*(9–10), 344–356. https://doi.org/10.1177/0263617420948699

Mohammed, M. A. A., Salmiaton, A., Azlina, W. A. K. G. W., Amran, M. S. M., Fakhru, A., & Taufiq-yap, Y. H. (2011). Hydrogen rich gas from oil palm biomass as a potential source of renewable energy in Malaysia. *Renewable and Sustainable Energy Reviews*, *15*(2), 1258–1270. https://doi.org/10.1016/j.rser.2010.10.003

Musah, M., Yisa, J., Suleiman, M. A. T.,Mann, A. and Shaba, E. Y. (2018). Study of isotherm models for the adsorption of Cr (VI) ion from aqueous solution onto Bombax buonopozense Calyx activated carbon. *Lapai Journal of Science and Technology*, *4*(1), 22–32.

Mutanekelwa, W., Okumu, F., & Andika, D. (2022). Adsorption Behaviour of Selected Biochar for Cadmium in Black Soldier Fly (Hermetia Illucens) Larvae Fed On Contaminated Organic Waste. *Journal of Material Sciences & Manufacturing Research*, *3*(3), 1–6.

Nguyen, H. H. T., Choi, Y. H., Kim, E. B., Jeong, Y. H., Lee, J. W., Park, K. H., Woo, Y. J., Ameen, S., & Kwak, D. H. (2025). Investigation of Pb(II) adsorption by amine group enriched chitosan encapsulated iron oxides doped biochar for soil remediation. *Carbon Trends*, *19*(January), 100465. https://doi.org/10.1016/j.cartre.2025.100465

Rajoriya, S., Haquiqi, A., Chauhan, B., Tyagi, G., & Pundir, A. S. (2020). Influence of Adsorption Process Parameters on the Removal of Hexavalent Chromium (Cr (VI)) from Wastewater : A Review. *Journal of Environmental Treatment Techniques*, *8*(2), 597–603.

Shixiang Zhao, N. T. and X. W. (2020). Absorption of Cu(II) and Zn(II) from Aqueous Solutions onto Biochars Derived from Apple Tree Branches. *Energies*, (Ii).

Singh, R., & Bhateria, R. (2020). Optimization and Experimental Design of the Pb 2 + Adsorption Process on a Nano-Fe 3 O 4 - Based Adsorbent Using the Response Surface Methodology. *ACS Omega*, *5*, 28305–28318. https://doi.org/10.1021/acsomega.0c04284

Syarifuddin, S., Heryanto, H., Suryani, S., & Tahir, D. (2024). Biochar from diverse wastes: A comprehensive bibliometric analysis of heavymetal adsorption in wastewater. *Desalination and Water Treatment*, *317*(December 2023), 100089. https://doi.org/10.1016/j.dwt.2024.100089

Tian, X., Xie, Q., Chai, G., & Li, G. (2022). Simultaneous adsorption of As (III) and Cd (II) by ferrihydrite - modified biochar in aqueous solution and their mutual effects. *Scientific Reports*, (Iii), 1–11. https://doi.org/10.1038/s41598-022-09648-1

Wang, Y., Qiu, M., Tay, C. C., Liu, Z., Wang, W., & Hu, B. (2025). Efficient adsorption and reduction of Au (III) to gold particles using cost - effective chitosan functionalized cellulose nanofiber. *Carbon Research*, *4*(12), 1–11. https://doi.org/10.1007/s44246-024-00176-3

Yang, Z., Wang, J., Zhao, N., Pang, R., Zhao, C., Deng, Y., & Yang, D. (2024). A novel biochar - based 3D composite for ultrafast and selective Cr (VI) removal in electroplating wastewater. *Biochar*. https://doi.org/10.1007/s42773-024-00338-x